

HYGROTHERMAL BEHAVIOUR OF PREFABRICATED FAÇADE ELEMENTS FOR BUILDING RENOVATION

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ABSTRACT

Since 2015, the requirements in terms of energy performance imposed by the EPBD regulations in Flanders also apply to existing buildings undergoing major renovation works. In this context, prefabricated façade components have a large potential for renovating the existing building stock in a fast and repeatable way.

Depending on the building structure, the existing façade can be demolished and replaced by new elements (skeletal structure) or it can (partly) be preserved. In that case, the new elements are installed against the existing wall and typically an adaption layer, e.g. mineral wool, is used to fill the void between the new element and the existing wall. This is done for load-bearing façades or cavity walls where the inner cavity leaf is preserved.

In this paper the hygrothermal behaviour of prefabricated façade elements that are placed in front of an existing wall is studied. More specifically, the paper focuses on what happens when the existing wall is humid, e.g. because it is left unprotected after the existing outer cavity leaf was demolished or when the new element is installed in front of a massive masonry wall subjected to wind driven rain. The paper focuses both on timber frame elements and on elements with integrated vacuum insulation panels, and evaluates the impact of different choices in the design on the risk of degradation of the elements.

INTRODUCTION

The energy use for heating and cooling of buildings has to decrease by 2050, according to the EU. To reach this goal, prefabricated envelope modules can be applied for the renovation of the existing building stock. The systems combine thermal insulation, acoustic performance, fire resistance, air- and water tightness, outer and inner finishing layers in one element. Benefits are e.g. the functionality during renovation works, the possibility of integrating windows, HVAC and energy systems and the limited number of activities on site. Especially for buildings that have a modular façade these system are

promising e.g. offices, multi-storey residential buildings, social housing, schools etc.

Despite of these advantages, prefabricated systems are rarely used in the Belgian renovation market. The building industry points out that there is lack of knowledge on a technical level, which hinders full application.

In the past, the possibilities of using prefabricated façade elements for renovation were investigated and demonstrated in several European research projects, including the main projects Annex 50 and TES Energy Façade. In Annex 50, four different approaches were elaborated for the renovation of residential apartment buildings: a timber frame element with integrated technical devices (ventilation tubes), a timber frame element with integrated thermal solar collectors and two metal frame panel systems (Miloni et al, 2011). The TES Energy Façade project focused on timber frame elements. The system typically consists of an adaption layer that fills the void between the existing construction and the new element, a TES module and a cladding layer (Fig.1). The TES module can either be a closed module, including a panelling layer at the backside of the module, or an open module (Table 2). Technical requirements such as fire safety, acoustics, HVAC, wind- and watertightness... are included in the system.

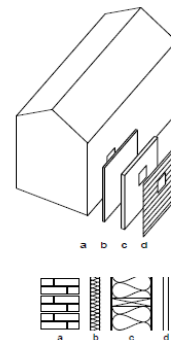


Figure 1: Basic TES façade element with a: existing wall, b: adaption layer, c: TES element, d: cladding (TES Energy Façade, 2010-2013)

In these research projects, the hygrothermal behaviour of the prefabricated modules is only

briefly discussed. The TES Energy Façade project distinguishes between two main groups of existing buildings: skeleton structures, which are less problematic because usually an entire new façade is installed, and massive external wall structures which mostly stay in place but often have a high moisture content caused by driving rain, capillarity or limited drying possibilities. The project mentions that the drying capability has to be ensured by using diffusion open materials on the exterior side of the elements and that construction materials with a good moisture absorption capacity such as cellulose or wood fibre products are preferred. The maximum material moisture content must not exceed 20% of the TES timber construction (TES EnergyFaçade, 2010-2013).

In this paper the hygrothermal behaviour of prefabricated façade elements is studied. More specifically the paper focuses on what happens when an initially humid existing wall is drying out, e.g. when the inner cavity leaf is left unprotected after the outer cavity leaf was demolished or when the existing wall has moisture problems resulting e.g. from rising damp or wind driven rain. The first part of the paper focuses on the impact of different design choices on the hygrothermal behaviour of timber frame elements. In the second part of the paper the possibilities of integrating vacuum insulation panels in a prefabricated element are explored. The integration of VIPS might be very promising since the element thickness can be reduced while obtaining a high insulation value. In literature, some examples of VIPS integrated in prefabricated elements can be found in (BINE, 2011, Panic et al, 2009).

INITIAL MOISTURE CONTENT OF THE EXISTING FAÇADE

To estimate the initial moisture content of the existing construction, the maximum and average moisture content were assessed after 15 years of exposure to the outdoor climate. Hygrothermal simulations were performed with the 1D HAM model WUFI PRO 5.3. The results are shown in Figure 3. The weather data of Brussels (Belgium) was used, the indoor climate was based on EN 13788 (humidity class 3). Simulations started on October 1st, a one hour time step was used.

Figure 2 shows the average and maximum moisture content after 15 years of exposure to the outdoor climate for a massive masonry wall, a concrete wall and a cavity wall. The estimated moisture content is highest for SW oriented walls. This is expected since this orientation receives the highest amount of wind driven rain. Furthermore, taller façades are subjected to a higher rain load leading to a higher

moisture content. Besides the SW orientation also the N orientation is interesting to look at since the drying potential is usually limited due to the absence of solar irradiation.

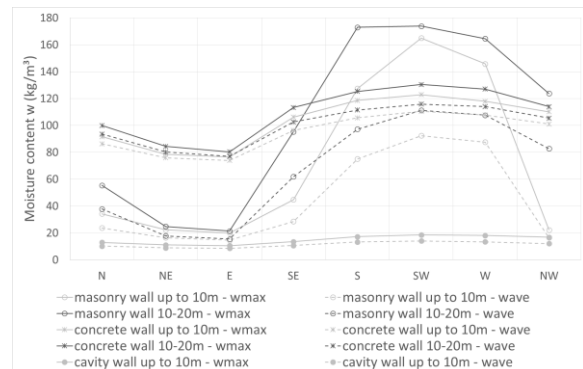


Figure 2: Estimated initial moisture content after 15 years exposure (wmax : maximum moisture content, wave : average moisture content)

Massive masonry walls show the highest moisture content: the max. moisture content is resp. 173,9 kg/m³ and 55,4 kg/m³ for a SW and N oriented wall. For the concrete wall similar trends are observed but there is a smaller deviation between the different cases. The max. moisture content for SW and N oriented façades is resp. 130,4 kg/m³ and 100 kg/m³.

The moisture content of the cavity wall is much lower than that of the other walls. However, usually the outer cavity leaf is demolished before installing the new façade elements and often the inner cavity leaf remains unprotected before installing the new façade elements. Therefore, Figure 3 shows the moisture content of the inner masonry cavity leaf (14 cm thick) during one year of exposure to the outdoor climate (façade height < 10m). The max. moisture content of a SW and N oriented façade is respectively 189,7 kg/m³ and 41,4 kg/m³, on average it is respectively 64,0 kg/m³ and 15,7 kg/m³.

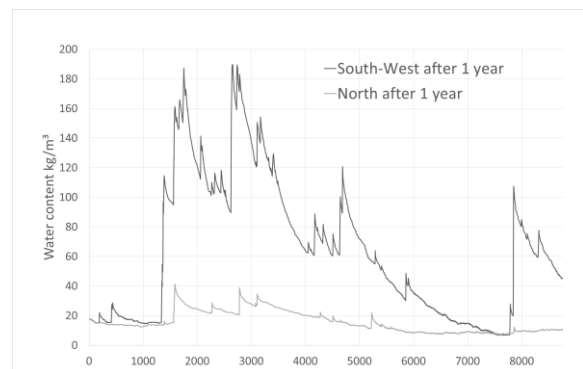


Figure 3 : Total moisture content of an inner masonry cavity leaf exposed to the outdoor climate during one year.

In the following simulations, the maximum moisture content is used as an estimation of the initial moisture content of the existing façade.

EVALUATION CRITERIA

In order to evaluate the risk of degradation of wood-based materials, the TOW (= 'Time of Wetness') criteria of (Viitanen, 1996) are used :

- TOW 20/5: the number of hours during which the moisture content exceeds 20% kg/kg and the temperature $> 5^{\circ}\text{C}$ should be limited to one month per year or max. 720 hours/year to prevent risk of mould growth.
- TOW 25/10 : the number of hours during which the moisture content exceeds 25% kg/kg and the temperature $> 10^{\circ}\text{C}$ should be limited to one week per year or max. 168 hours/year to prevent the risk of wood rot.

The VTT model of Hukka en Viitanen in which the growth development is expressed by a mould index, was used to further estimate the risk of mould growth. The updated version of the model that can be applied to other building materials was used (Vereecken, 2012). A possible decrease of the mould index during unfavourable conditions was not included in the evaluation, as Vereecken states that this effect is not always reliable (Vereecken, 2012). Table 1 shows the 7 mould index classes used in the model.

Table 1: Mould index classes in the VTT model (from Vereecken, 2012)

INDEX	GROWTH RATE	DESCRIPTION
0	No mould growth	Spores not activated
1	Small amounts of mould on surface	Initial stages of growth
2	<10% coverage of mould on surface	
3	10-30% coverage of mould on surface	New spores produced
4	30-70% coverage of mould on surface	Moderate growth
5	>70% coverage of mould on surface	Plenty of growth
6	Very heavy, dense mould growth covers nearly 100% of surface	Coverage around 100%

HYGROTHERMAL EVALUATION OF TIMBER FRAME FAÇADE ELEMENTS

In the first part the hygrothermal performance of an open and closed timber frame façade element that is installed in front of an existing inner masonry cavity leaf, is evaluated. Table 2 shows the typical construction of these modules. A ventilated cladding

is considered for both elements. The cladding layer was ventilated with an air change rate of 10 ACH.

Table 2: Closed and open façade module (based on TES Energy Façade, 2010-2013)

	10mm plaster 140 mm existing inner cavity leaf 160 mm cellulose insulation 15 mm wood fibre board 40 mm air layer 40mm 20 mm wooden, ventilated cladding
(a) Open façade module – base case	
	10 mm plaster 140 mm existing inner cavity leaf 50 mm cellulose adaption layer 18 mm OSB 3 160 mm cellulose insulation 8 mm wood fibre board 40 mm air layer 20 mm wooden, ventilated cladding
(b) Closed façade module – base case	

According to TES, the adaption layer typically is a 3 to 5 cm cellulose or mineral wool layer (TES EnergyFaçade, 2010-2013). The thickness of the insulation layer in the module is based on compliance with the Flemish EPBD regulations ($U_{\max, \text{walls}} = 0,24 \text{ W/m}^2\text{K}$). The material properties used in the simulations can be found in Table 3 and Figure 4. For the cellulose fibre, mineral wool, masonry and OSB, a constant water vapour resistance factor was used.

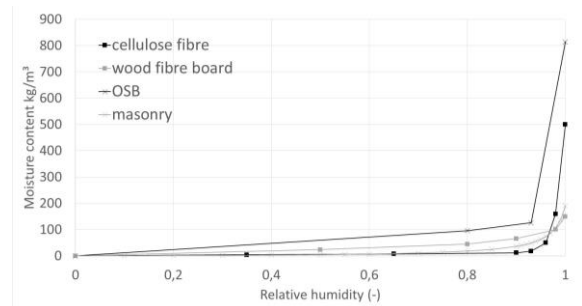


Figure 4 : Material moisture content in kg/m^3 (based on WUFI material database)

Table 3: Material properties (based on WUFI material database)

	RHO (KG/M^3)	C_p (J/KGK)	λ_{DRY} (W/MK)	μ (-)
Wood fibre board	300	1500	0.05	12,5
Cellulose	70	2500	0.04	1,5
Mineral wool	60	850	0.04	1,3
OSB	595	1700	0.11	165
Masonry	1900	2500	0.6	10

The weather data of Brussels (Belgium) was used. The indoor climate was based on EN 13788 (humidity class 3). Simulations started on October 1st, a one hour time step was used.

Open façade module

Table 2 shows the construction of the open façade module that is used in the base case simulation model. The evolution of the moisture content in this element during five years is shown in Figure 5 for a SW oriented façade. It is clear that the initially humid masonry leaf is drying out in the first two years. Due to this vapour flow, the moisture content in the wood fibre board is raised during the 1st year.

In order to evaluate whether the increased moisture content in the wood fibre board may give rise to degradation, its moisture content in %kg/kg is shown in Figure 6 during a period of five years.

In the base case, cellulose insulation is used as an adaption layer. In this case the moisture content often exceeds 20% kg/kg which indicates there is a risk of mould growth. Especially in the first year there is a risk of rot. These risks increase when mineral wool is used as an adaption layer material: the moisture content increases to about 44% kg/kg in the first year. This was expected as mineral wool has no moisture buffering capacity compared to cellulose.

When looking at a north oriented façade we can observe that the degradation risk is slightly lower, especially during the first year after dry-out. This is explained by the lower initial moisture content (41,4 kg/m³) compared to a SW oriented façade.

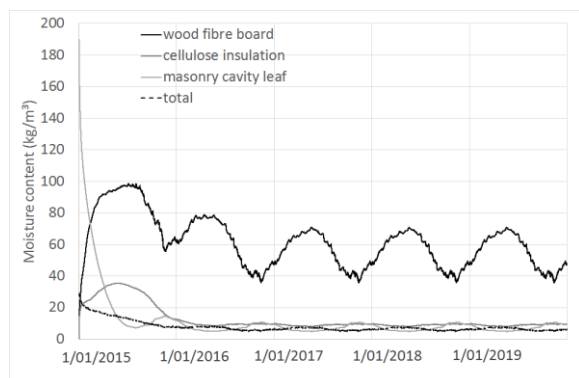


Figure 5 : Moisture content in kg/m³ in an open façade module (base case) during five years

In order to decrease the possible degradation of the wood-fibre board, the effect of a vapour barrier between the masonry cavity leaf and the new module was evaluated. Figure 6 shows that the use of a vapour barrier with an sd-value of 1m already has a positive effect on the moisture content in the wood-fibre board. These results are confirmed when

looking at Figure 7, that shows an estimation of the mould index based on the VTT model during the first year. Figure 7 shows that the base case model leads to a mould index of almost 5, while adding a vapour barrier with an sd-value equal to resp. 1m and 10m may reduce the mould index to 1,5 and below 1.

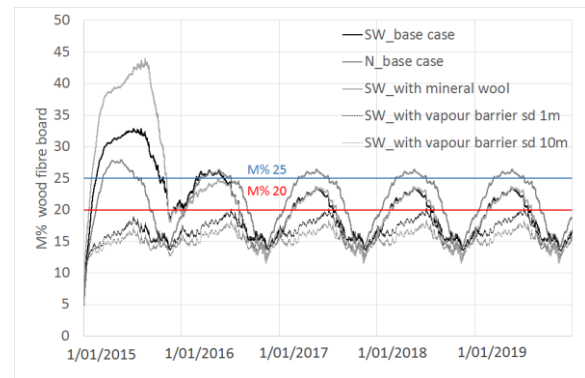


Figure 6 : Moisture content in %kg/kg in the wood fibre board during five years

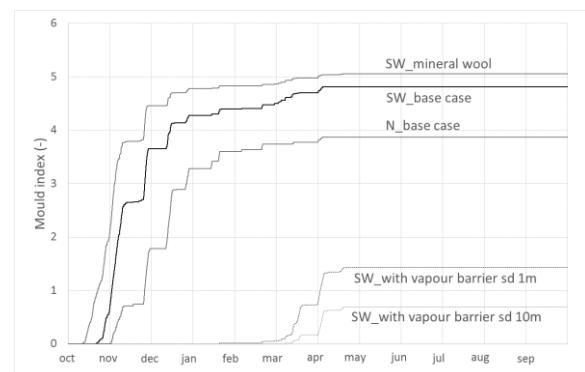


Figure 7 : Evolution of the mould index based on the VTT model during the 1st year after drying out

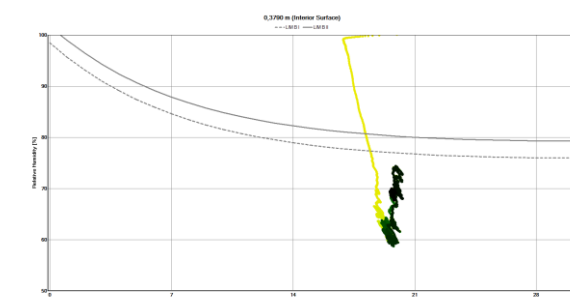


Figure 8: Isopleths on the inner surface of the masonry cavity leaf for an open module with a vapour barrier (sd-value 10m)

By adding a vapour barrier to the module, part of the vapour will dry out to the inside of the building. It must be checked that this does not lead to a mould growth risk at the inside surface. Figure 8 shows the isopleths on the inner surface of an open module with a vapour barrier (sd-value 10m), calculated in

WUFI. The limiting isopleth is only exceeded during the first period after the existing cavity leaf is drying out (yellow colour) and therefore it is considered that the risk of mould growth is limited.

Closed façade module

In Table 2, the construction of the closed façade module that is used for the base case simulation model is given. Figure 9 shows the moisture content in the wood fibre board and the OSB panel for a SW oriented module, a N oriented module, and a SW oriented module filled with mineral wool instead of cellulose.

For the SW base case model, during the first year of drying out, there is only a risk of mould growth and rot in the OSB panel. For the N orientation, there is no risk of degradation. Because the mineral wool has no moisture buffering capacity, the risk is higher both in the OSB panel and in the wood fibre board, during the first year for this case. These observations are confirmed by Figure 10, that shows the highest mould index for the module with mineral wool. There is no risk of mould in the north oriented module (mould index zero).

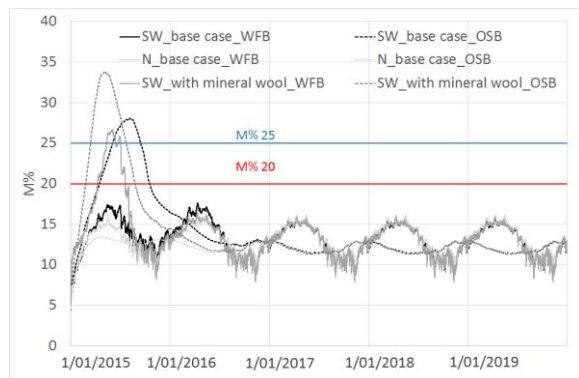


Figure 9 : Moisture content in %kg/kg in the wood fibre board and the OSB board during five years

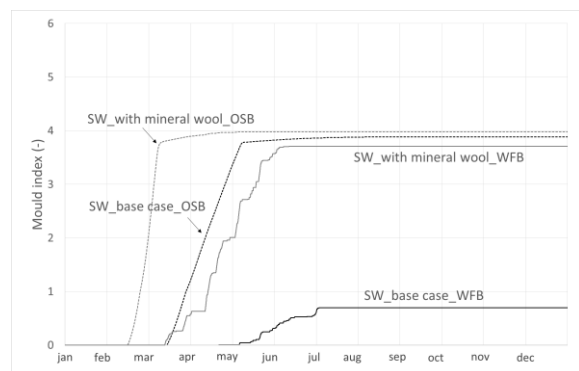


Figure 10 : Evolution of the mould index based on the VTT model during the 1st year after drying out

In a second step, the OSB panel is firstly replaced with a 4 times more vapour tight OSB panel (μ -value

650 instead of 165) and secondly with a wood fibre board (μ -value 12,5). Figure 11 and 12 respectively show the moisture content and the evolution of the mould index in comparison with the base case model.

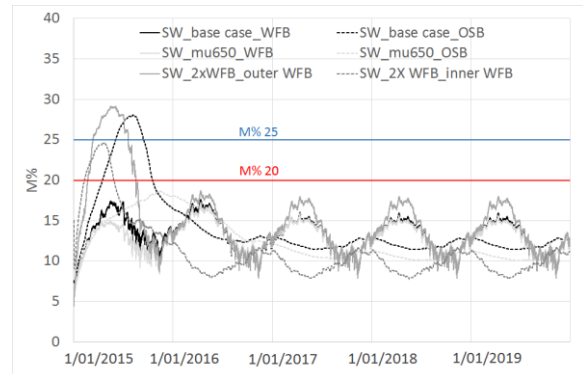


Figure 11 Moisture content in %kg/kg in the wood fibre board and the OSB board during five years

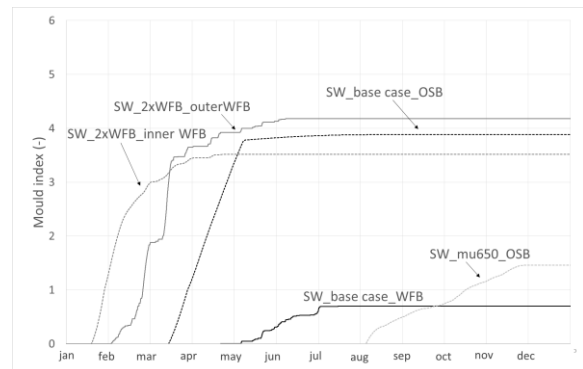


Figure 12 : Evolution of the mould index based on the VTT model during the 1st year after drying out

When a more vapour tight OSB panel is used, the moisture content in the OSB is damped (Fig.11), eliminating the risk of degradation of both the OSB and the wood fibre board. The estimated mould index of resp. the OSB and wood fibre board move from 1 (base case) to 0, and from 4 (base case) to 1,5 (Fig.12).

The use of a wood fibre board instead of an OSB panel for the inner panelling layer, results in a larger vapour flow into prefabricated module, and thus in a higher moisture peak in the outer panel, and a slightly smaller peak in the inner panel. This may result in a larger risk of degradation (estimated mould index around 4) (Fig. 11 and 12).

DESIGN OF A FAÇADE ELEMENT WITH INTEGRATED VIP PANELS

In the second part of this paper the design of a façade module with integrated vacuum insulation panels (VIPS) is discussed. The integration of VIPS

in prefabricated façade elements has some advantages :

- Unlike traditional prefabricated elements like TES, the limited thickness and excellent insulation value are interesting for renovation purposes where the additional wall thickness that is allowed, is limited.
- Due to the integration in a prefabricated panel, protection of the VIPS during installation is ensured.

Preliminary simulations based on existing prefabricated systems showed the potential of including VIPS in prefabricated modules. However these panels have a high vapour resistance due to vapour resistant aluminium foil that will hinder the drying potential of the existing wall and may lead to interstitial condensation. Because of that, the installation of moisture sensitive panels between the existing wall and the VIPS should be avoided (Martens, 2015).

Table 4: Façade modules with integrated VIP, based on (Martens, 2015)

	10 mm plaster 340 mm existing masonry wall 30 mm MW adaption layer 10 mm PUR 40 mm vacuum insulation panel 7 mm PUR 20 mm plywood board
	10mm plaster 340 mm existing masonry wall vapour retarder (sd 10m) 30 mm MW adaption layer 10 mm PUR 40 mm vacuum insulation panel 7 mm XPS 20 mm HPL plate
	10mm plaster 340 mm existing masonry wall 30 mm MW adaption layer 34 mm fibre cement board 40 mm vacuum insulation panel 7 mm XPS 10 mm HPL plate

Therefore, the initial design consists of a levelling layer in mineral wool, a PUR layer that protects the VIPS and a plywood layer that ensures the stiffness

of the module and that is placed at the outside of the façade module ((a) in Table 4). The U-value of the initially designed panel was calculated 0,10 W/m²K (without side effects). Depending on the type of fixation system, the overall U-value was situated between 0,12 and 0,16 W/m²K (Martens, 2015).

In the next sections, the evolution of the initial design of this façade module is discussed, based on the hygrothermal performance. In all simulations the module is installed in front of an existing humid masonry façade (SW orientation, 34 cm thick, height < 10 m). Note that because 1D simulations are used, eventual risks at the joints of the VIP-panels are not taken into account.

Risk of degradation of outside plywood board

Figure 13 shows that, although in the initial design the plywood board can dry out to the outside, the moisture content of the plywood often exceeds 20% kg/kg and 25% kg/kg, both for panels with and without ventilated cladding. Consequently there still exists a risk of degradation (mould growth and rot). Therefore the plywood board is replaced by a HPL (High Pressure Laminate) board that is moisture resistant and that can be used as a finishing layer.

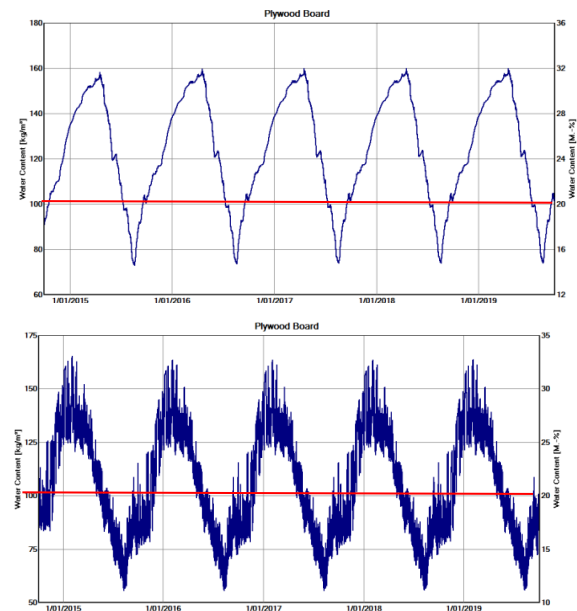


Figure 13 : Water content in the plywood board with (upper) and without (under) ventilated cladding during 5 years (—20% kg/kg)

Condensation risk of protective insulation layer

Secondly, the relative humidity of the PUR layer that protects the VIPS behind the cladding layer is studied. Simulations showed that condensation is possible ($RH > 100\%$) and therefore the PUR layer is replaced with an XPS layer which is more moisture resistant.

Zone between VIP element en existing wall

Next, the risk of interstitial condensation that may occur against the VIP surface when the existing masonry wall is drying out, is evaluated. This is done by adding a thin (1mm) fictitious water layer with a large moisture capacity (Fig.14). It was considered that the maximum amount of interstitial condensation at the VIP surface should not exceed 0,200 kg/m² in order to prevent water run-off. This was based on evaluation criteria for interstitial condensation for non-hygroscopic, non-capillary materials (Martens, 2015).

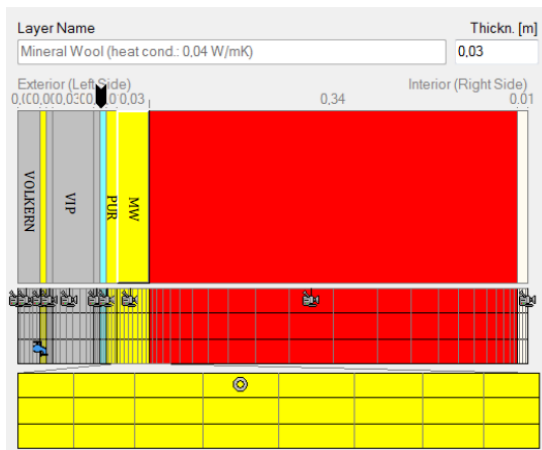


Figure 14 : WUFI model used for the evaluation of interstitial condensation (blue = fictitious air layer)

Figure 15 gives the water content of the fictitious air layer. The results show a large condensation risk on the inner surface of the VIP layer, due to its high vapour tightness. The highest risk corresponds to a mineral wool levelling layer with a thickness of 30 mm (initial design). Figure 15 shows that the conditions improve somewhat when reducing the thickness of the levelling layer to respectively 20 mm and 10 mm but there is still a high risk on interstitial condensation (water content often $> 200 \text{ g/m}^2$ or $> 200 \text{ kg/m}^3$).

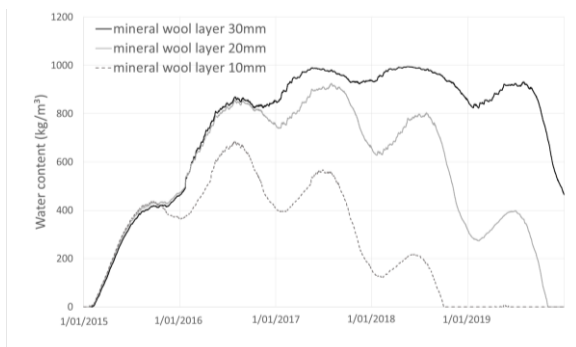


Figure 15 : Water content in fictitious air layer in case of a mineral wool levelling layer with thickness 30mm - 20mm - 10mm during 5 years

Therefore, the effect of a vapour retarder between the existing masonry wall and the mineral wool layer is studied ((b) in Table 4). Figure 16 shows that the water content in the fictitious air layer at the inside of the VIP is lower than 200 kg/m^3 when integrating a vapour barrier with an sd-value of 10 m.

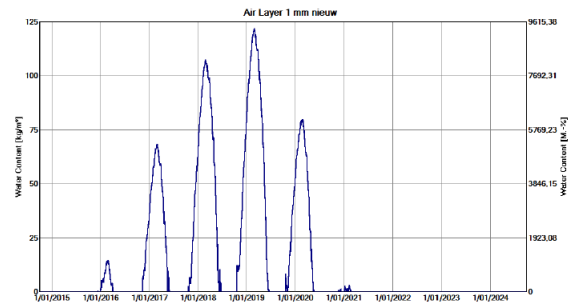


Figure 16 : Water content in fictitious air layer
with integrated vapour retarder (sd-value 10 m)
during 10 years

However, adding a vapour retarder between the levelling layer and the existing masonry wall prevents the wall from drying out towards the outside. The higher vapour flux towards the inside might lead to mould growth at the inside surface.

Figure 17 shows the isopleths at the inner surface calculated in WUFI. The limiting isopleth is only exceeded during the first period after the existing masonry wall is drying out (yellow colour) and therefore it is considered that the risk of mould growth is limited.

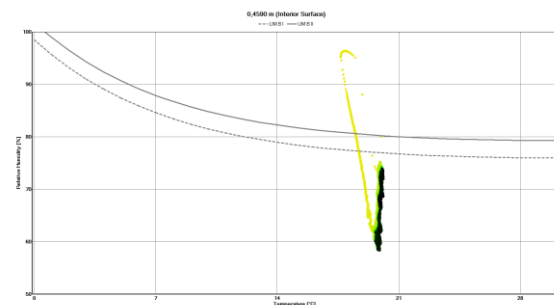


Figure 17 : Isopleths on the inner surface of the 34 cm thick masonry wall with integrated vapour barrier (sd-value 10m) in the module

From a practical point of view however, the integration of a vapour retarder at the back side of a façade module may be difficult. The vapour retarder should be installed on the existing wall before the façade elements are installed. An alternative solution consists of integrating a moisture buffering layer in the prefabricated module, that allows buffering the vapour flow, that is drying out from the existing masonry wall. Therefore, the supportive panel that

was placed at the outside of the module, is moved to the inside of the module and is replaced by a fibre cement board. The HPL panel is still used as finishing layer and watertight layer, but has a reduced thickness ((c) in Table 4).

Figure 18 shows the water content in the fictitious air layer between the fibre cement board and the VIP. As the water content remains lower than 200 kg/m³ it is considered that there is no risk of interstitial condensation. When looking at the relative humidity of the fibre cement board it can be observed that the RH steeply increases when the masonry wall starts to dry out (Fig.19). This indicates that the fibre cement board is almost saturated. An evaluation of the isopleths at the interior surface of the existing masonry wall shows that there is no risk of mould growth.

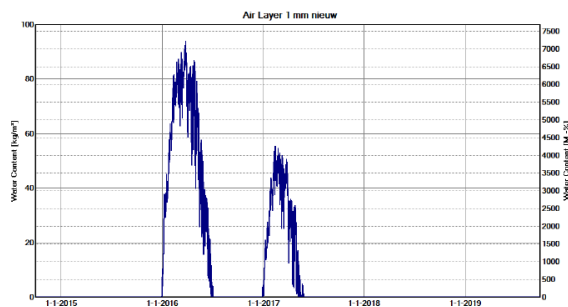


Figure 18 : Water content in the fictitious air layer during 5 years, when using a fibre cement board

Cellulose adaption layer

Finally, the effect of using cellulose instead of mineral wool for the adaption layer is studied. As cellulose has a larger moisture capacity, it was expected that it could help in reducing the moisture content of the fibre cement board. Figure 19 shows that this effect is limited: the use of cellulose insulation reduces the relative humidity slightly, but overall it stays very high. Although the fibre cement board is considered moisture resistant, further analysis should clarify whether a persistently high relative humidity will adversely affect its durability.

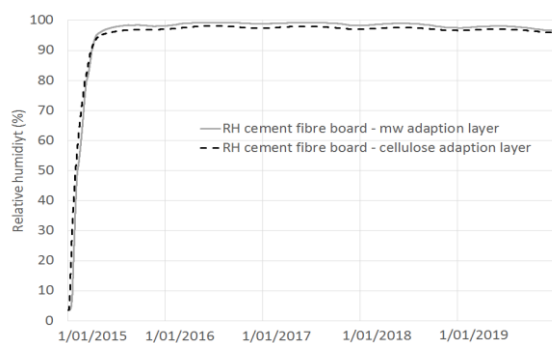


Figure 19 : Evolution of the RH in the fibre cement board during 5 years, when using mineral wool and cellulose for the adaption layer

CONCLUSION

Hygrothermal evaluation showed that it is recommended to install a vapour barrier between the timber frame element and the humid existing façade. For open elements the use of vapour retarder with sd-value of 1m already had a positive effect, for closed elements this could be realized by using an OSB panel with a high diffusion resistance. The use of cellulose insulation proved to have a moisture buffering effect. The integration of vapour tight VIP panels in prefabricated modules resulted in a risk of interstitial condensation at the inside of the panel. Simulations showed that this risk could be reduced by integrating a vapour barrier or using a supportive panel with moisture buffering characteristics such as a fibre cement board.

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REFERENCES

- Miloni, R., Grischott., N, Zimmerman, M. 2011. Annex 50: Prefabricated Systems for Low Energy Buildings: Retrofit Module Design Guid, International Energy Agency (IEA).
- TES Energy Façade. 2010-2013. Prefabricated timber based building system for improving the energy efficiency of the building envelope.
- BINE Informationsdienst. 2011. Projektinfo 04/08: Building refurbishment – highly insulative large elements.
- Panic, E., Fürstenberger, A., Lang, G., Pachner, P. 2009. Erste Altbauanierung auf Passivhausstandard mit VIPs.
- Martens S. 2015. Detaillering van geprefabriceerde gevelpanelen in renovatietoepassingen met VIP's. Masterthesis, UGent (in Dutch).
- Vereecken E. 2012. Review of mould prediction models and their influence on mould risk evaluation. Building and Environment 51: 296-310.
- Viitanen, H. 1996. Factors affecting the development of mould and brown rot decay in wooden material and wooden structures. Effect of humidity, temperature and exposure time. The Swedish University of agricultural Sciences, Department of Forest Products.